Triggering the Formation of Massive Clusters

Bruce G. Elmegreen

IBM Research Division, T.J. Watson Research Center, Yorktown Hts., NY 10598 USA bge@watson.ibm.com

Abstract. There are at least 2 distinct mechanisms for the formation of young massive clusters (YMC), all of which require galactic-scale processes. One operates in harrassed fragile galaxies, in the dense cores of low mass galaxies, at the ends of spiral arms, or in galactic tidal shocks where transient and peculiar high pressures make massive clouds at high densities. The result of this process is usually only one or two YMC without the usual morphologies of local star formation, i.e., without hierarchical structure and a continuous power law distribution of cluster masses up to the largest mass. The other operates in the more usual way: continuously for long periods of time in large parts of the interstellar medium where the ambient pressure is already high as a result of the deep potential well from background stars and other gas. This second process makes clusters in a hierarchical fashion with size-of-sample effects, and tends to occur in nuclear rings, merger remnants, and even the ambient ISM of normal galaxies if the star formation rate is high enough to sample out to the YMC range.

1.   Triggering Low Mass Clusters

Local clusters often show the signatures of high-pressure triggering: they form in the heads of pressure-swept, cometary clouds that are adjacent to older massive stars, or they form in compressed layers or shells between expanding HII regions or wind bubbles and the surrounding gas. Examples of the former include Orion (Bally et al. 1987; Lada, et al. 1991; Reipurth, Rodriguez & Chini 1999), the Eagle nebula (Hester et al. 1996), the rho Oph core (de Geus 1992), and many places in the clouds surrounding 30 Dor in the LMC (Walborn et al. 2002). Examples of the latter include the Carina nebula (Brooks, et al. 1998, 2001), the Rosette nebula (Phelps & Lada 1997), and other regions near 30 Dor. A list of likely triggered regions is in Elmegreen (1998).

Sometimes clusters form at the tips of elongated clouds with no obvious pressure source nearby. IC 5146 looks like this (Lada, Alves & Lada 1999): it is a long, filamentary cloud with most of the star formation near the eastern tip. Another example is in the Taurus region where most of the famous filaments have their star formation toward the east (Elmegreen 2002), often with short-lived molecules at these places, suggesting recent compression (Hartquist et al. 2001). In these places, the star formation is occurring at the most vulnerable places in the cloud where stray pressure bursts would have the greatest cross section

for interaction. Even if these pressure sources cannot be identified yet, perhaps because they were stray supernova whose other signs have long disappeared, the peculiar positions of star formation suggest some type of triggering was involved. In the case of Taurus, the pressure seems to have come from the Orion OB association.

2.   Triggering by Random Pressure Bursts

The probability that random pressure excursions trigger star formation is pretty low, especially for dense clusters of moderate mass. This conclusion comes from the probability distribution function for pressure excursions of a certain magnitude. If we consider a pressure source like an HII region, supernova or wind-swept bubble, the radius increases with time as $R(t)$. This function corresponds uniquely to a pressure dependence $P(t)$ for each type of source, and thus there is a relation between volume and pressure: $V(P)$. If these pressure bursts occur at a constant rate, then the number density of small regions having a certain pressure is proportional to the inverse of the pressure derivative: $n(P) \propto 1/\left(dP/dt\right)$. This comes from the one-to-one correspondence between pressure and time, and from the resulting equality between the number distribution of pressure events $n(P)dP$ between P and $P + dP$, and the time distribution of pressure, $P(t)dt$ between t and $t + dt$ for constant rate $P(t)$. This number density $n(P)$ combines with the volume function, $V(P)$, to give the filling factor of regions with pressure P: $f(P) = n(P)V(P)$ in linear intervals dP.

For HII regions, $f(P) \propto P^{-4.17}$, for bubbles and supershells, $f(P) \propto P^{-4.5}$, and for the pressure-driven snowplow phase of supernovae, $f(P) \propto P^{-5.2}$. These relations come from the usual expansion laws for these region, $R(t)$ (e.g., Weaver, et al. 1977; Cioffi et al. 1988). The summed contributions from these relations preserve the approximate power-law form, $f(P) \simeq AP^{-4.5}$ or so, for constant of proportionality A. If the summed filling factor from all expansions is unity, then $1 \sim \int AP^{-4.5}dP$, giving an average ISM pressure $P_{ave} = 1.4P_{min}$ for minimum pressure P_{min}, and $f(P) = 1.15\left(P/P_{ave}\right)^{-4.5}/P_{ave}$. From this result we can determine the probability that the pressure is between P and $P + dP$, measured as the volume filling factor, $f(P)dP$ for pressure in this range. Thus the probability the pressure exceeds 10 times the average is $0.31\left(0.1\right)^{3.5} \sim 10^{-4}$, and the probability the pressure exceeds 2 times the average is $0.31\left(0.5\right)^{3.5} \sim 0.03$. These are very small probabilities because the pressure from a power source decreases rapidly during the expansion to larger volumes. As a result, significant *random* pressure bursts from HII regions, supernovae, windy bubbles, and supershells are generally weak, on the order of a factor of 2 or less, although they may be frequent. This means that *pressure triggering from specific sources is usually very localized – in the same cloud complex, especially if what is triggered is a dense star cluster at a typically high pressure.*

A similar result may be gleaned from figure 3 in Kim, Balsara, & MacLow (2001), which shows the probability distribution function for pressure in a turbulent medium. This function is approximately log-normal with a range of a factor of ~ 2 in either direction about the dominant pressure and a small plateau at $10\times$ the dominant pressure from the young supernova remnants. Again it is

clear that large pressure excursions around the average ISM pressure should be rare.

3. Energy requirements for triggering YMCs

Another property of pressurized triggering can be inferred from the energy requirements. For pressure to be important in cloud formation, the energy to move the gas has to be on the order of $E \sim PV \sim Mv^2$ for ambient pressure P, moved volume V, moved mass M, and ambient velocity dispersion v. With $v \sim 7$ km s^{-1}, the formation of a YMC from a 10^6 M$_\odot$ cloud requires 10^{51} erg of energy during cloud formation. Moreover, this energy has to be convergent so that ambient gas is compressed into a cloud, not divergent like an explosion. We see from this that only large clusters can trigger other large clusters, and again that stray explosions are unlikely triggering sources in main galaxy disks, primarily because of their divergent nature. This means that an isolated YMC in a main galaxy disk was probably not triggered by compression from a stray explosion of the most common type. Instead we should look for a history of globally convergent flows, such as kpc-scale instabilities, galaxy-wide turbulence, or galaxy interactions. In the absence of such converging flows, massive clusters need high densities and pressures in the *ambient* medium, as is often the case in galactic nuclei. An example of nuclear triggering in a BCD galaxy could be Markarian 86 (Gil de Paz et al. 2000; 2002). Several other possible examples are in Saito, Kamaya, & Tomita (2000), and Cairós et al. (2001).

4. Large-Scale converging flows that do not seem to trigger YMCs

Galactic scale instabilities easily make $10^6 - 10^7$ M$_\odot$ clouds and these could in principle make YMCs but in the main disks of galaxies these regions are generally at the ambient pressure, which is low, and so their average densities are also low. That is, the stars they make are rarely collected into a ~ 5 pc size YMC but they are dispersed throughout a kpc region, like Gould's Belt, with a hierarchical pattern and dense clusters only on the smallest scales. Most clusters within several kpc of the Sun along with their associated "giant" molecular clouds are like this: they are only small pieces in much larger cloud complexes that dot the spiral arms with $\sim 2 - 3$ kpc separations (e.g., see review in Elmegreen 2002). Often the clusters themselves look triggered inside these clouds, on ~ 10 pc scales. For example, the outer Galaxy survey by Heyer et al. (2001) shows two large complexes, one associated with the HII regions W3/4/5 and another associated with NGC 7538. Inside these large regions, which are separated by $\sim 25° \sim 1$ kpc of relatively low CO emission, there are clusters and molecular clouds, many of which look triggered or perturbed by high pressure events. The IRAS point sources in the W3/4/5 region, for example (Carpenter, Heyer & Snell 2000), are mostly at the tips of cometary CO structures. No YMC's have formed although the total molecular masses in these two regions are large enough.

Clearly, galactic-scale triggering does not necessarily mean the formation of a YMC. Most galactic disk star formation processes are massive because their length scales are big, but they are not nearly high enough in pressure to make a YMC. The pressure inside a cloud core where a cluster forms is $\sim 0.1 GM^2/R^4$,

i.e., proportional to the squared column density. The density of a dense star cluster is typically $10^3 - 10^4$ M$_\odot$ pc^{-3}, so the column density is this multiplied by the radius, or $\sim 10^2 - 10^4$ M$_\odot$ pc^{-2}, with the upper end typical of YMCs. These column densities translate into pressures equal to $0.1G$ times the square of their values, which are in the range 10^{-10} to 10^{-6} erg cm^{-3}, or 10^6 to 10^{10} times Boltzman's constant, k_B. The ambient pressure in a typical disk is only $10^4 k_B$. Thus, massive high-pressure clouds need *highly* compressive, galactic scale events, not mildly compressive galactic-scale events. Instabilities involved with the formation of spiral arms and their regularly-spaced giant clouds are not usually dense enough to make dense massive clusters by themselves. Further collapse into massive dense cores, possibly in combination with pressurized triggering by very energetic older clusters, are required in addition.

5.   Galactic processes that may have triggered YMCs

5.1.   Main spiral disks

There are several examples of galactic processes that seem to have triggered the formation of a YMC. In NGC 6946, a YMC with 10^6 M$_\odot$ of stars lies at the end of a spiral arm, suggesting an asymmetric and perhaps unusually strong collapse of gas by an unbalanced gravitational force (Elmegreen et al. 2000; Larsen et al. 2002). Remarkably, another YMC in the same galaxy is at the tip of a different arm (S. Larsen, this conference), reinforcing this idea. Inside the first region, the history of star formation suggests a period lasting ~ 40 My producing distributed small clusters with an interruption of this mode ~ 15 My ago during which the YMC was the primary star-forming event. At ~ 5 My ago, the distributed star formation began again, lasting until today. Perhaps the imbalanced collapse made a massive dense cloud and the first generation of stars in this cloud compacted the remainder to make the YMC at extreme pressures (Larsen et al. 2002). Likely remnants of this cloud are still visible. The 30 Dor cluster in the LMC has a similar two-step structure with distributed, slightly older stars and clusters along the periphery, many of which seemed to have formed there, and a compact younger cluster in the center (Selman et al. 1999).

Although this outside-in morphology suggests convergent triggering, another possibility is that the dense cluster is a remnant of a prolonged coalescence of many small clusters that formed in a distributed fashion throughout the region. The age of the YMC in NGC 6946 has the average value of the ages of the smaller clusters around it, and the collision time works out for this model (Elmegreen et al. 2000). But in 30 Dor, the central cluster seems younger than the average of the other clusters, and in that case, the coalescence model does not work.

The 30 Dor region may have suffered from a large-scale compression resulting from its motion through the galactic halo (de Boer et al. 1998). This compression would have pushed on the whole eastern side of the LMC and made a giant CO cloud that extends for ~ 1 kpc south of 30 Dor, with 30 Dor at its northern tip.

Other small galaxies with YMCs look similarly perturbed (Billett, Hunter, & Elmegreen 2002). NGC 1569 is a classic example of a small galaxy with

YMC's (Waller 1991; Ho & Filippenko 1996a; Hunter et al. 2000) and it has a peculiar stream of HI extending from far outside the optical radius to the very point in the disk where the 2 YMC's are located (Waller 1991). It looks like this HI crashed into the disk and compressed the ambient gas to make the clusters out of the resulting massive dense clouds.

Large galaxies can be perturbed by collisions also. The NGC 2207/IC 2163 pair suffered a grazing collision with a peri-galacticon $\sim$ 40 My ago. One of these galaxies was perturbed in a prograde, in-plane sense, and its outer disk responded by falling inward for a half-epicycle and crashing against other disk material that did not fall in as quickly. As a result, a galactic-scale shock front formed having the overall shape of an pointed-oval or eye (Elmegreen et al. 1991). This shock front contains several YMC (Elmegreen et al. 2001).

5.2. Galactic nuclei

The centers of some low-mass galaxies have YMCs, as does the nuclear region of the Milky Way. NGC 4214 is a dwarf galaxy with a 4-5 My old YMC in the nuclear region (Leitherer et al 1996; Billett et al 2002). Other examples are NGC 1705 (Meurer et al. 1992; O'Connell et al. 1994; Ho & Filippenko 1996b), and the probable embedded clusters in NGC 5253 (Turner, Ho, & Beck 1998), He 2-10 (Conti & Vacca 1994; Kobulnicky & Johnson 1999), and NGC 2366 (Drissen et al. 2000).

The processes of collecting massive amounts of gas into dense nuclear clusters are not known. They could form by spontaneous gravitational instabilities in dense nuclear gas that is drawn in from the outer disk by asymmetric forces and viscous accretion.

5.3. Morphology and size of sample effects in YMC-triggered regions

Some of these examples of YMC triggering do not seem to satisfy the size-of-sample effects expected for a random ensemble of clusters. What is observed is that the YMC is much more massive than any other cluster in the galaxy or region. For the size-of-sample effect to apply, the YMC would have to be the most massive member of a continuous power law distribution of mass. Perhaps our impression that the size-of-sample effect does not apply in these cases is statistically insignificant because the number of violations like this is very small. For example, in the case of dwarf galaxies with unusually large YMCs, such as NGC 1569, it could be that the whole galaxy should be viewed as a member of the ensemble, along with other whole galaxies, and not just the individual clusters in one galaxy. Then, if we were to sample among many galaxies, we might expect that all of the clusters in the composite would exhibit a smooth power law mass distribution even if each galaxy alone has large deviations from this.

Nevertheless, the observations give the impression that some regions selectively produce YMC without making a proportional number of low mass clusters. A cluster mass distribution function in these regions gives a slope that is significantly flatter than -2 (for linear intervals of mass). This is the case in IC 2163 and NGC 2207 mentioned above, where the slopes are 1.85 ± 0.05 and 1.58 ± 0.12 (Elmegreen et al. 2001). The most massive two YMCs in IC 2163 are in the galactic tidal shock, and they have a mass comparable to the most massive

YMCs in the antennae, which contains $\sim 10\times$ more massive clusters overall. Thus the YMCs in IC 2163 do not appear to satisfy the normal size-of-sample relation given the small number of other clusters in this galaxy.

Clusters in these regions also look odd because they are not part of a hierarchical network of star formation consisting of small clusters or associations inside larger star complexes. This morphological issue is related to the size-of-sample problem. The YMCs are so large when the size-of-sample effect is violated that they completely dominate the region without any significant superstructure or substructure, as in a hierarchy. An analogy might be with Gould's Belt. A YMC can have all of the mass of stars in the local Gould's Belt put into a cluster as dense as the Trapezium cluster. As it is, the Trapezium cluster and others like it are a small part of the local hierarchy that has Gould's Belt on the largest scale, divided into OB associations, OB subgroups, and individual clusters on smaller scales.

5.4.   Summary: YMC triggering by galactic scale flows

YMCs have been found in *peculiar, high-pressure* regions including: (1) fragile galaxies like dwarf Irregulars undergoing interactions that produce relatively major disturbances; (2) short-lived tidal arms or caustics in the main disks of interacting galaxies; (3) the leading surface of the LMC that may be subject to ram pressure from motion through the Milky Way, and (4) gas collection points in the centers of small galaxies.

These regions tend to be small and form few clusters overall, so the YMCs do not appear to be accompanied by the usual power law distribution of numerous low mass clusters.

Proposed cluster formation processes in these regions include: (1) shock compression in a large part of a galaxy; (2) local compression and collapse from extragalactic cloud impacts, strong gravitational instabilities at the end of a spiral-arm, or colliding supershells (Chernin, Efremov, & Voinovich 1995); (3) coagulation of smaller clusters, or accretion to the galactic nucleus where long-term collection can produce a massive central concentration of gas at high pressure.

6.   YMC formation in disk regions with high ambient pressure.

The same processes of star formation that make small clusters in the solar neighborhood can make YMCs if the ambient pressure is high. Then massive self-gravitating cloud cores will have extremely large column densities and star formation in them can produce a massive cluster. These processes include turbulent fragmentation, sequential triggering, and spontaneous gravitational collapse.

High ambient pressures occur in nuclear rings, nuclear disks, and merger remnants. Giant clusters form as part of a statistical ensemble of clusters with a near-universal mass function, $n(M)dM = AM^{-2}dM$ for constant A that depends on the star formation rate (Elmegreen & Efremov 1997). The YMCs also tend to form in a hierarchical fashion (Zhang, Fall, & Whitmore 2001).

In this mode of cluster formation, there are several size-of-sample effects. First, the maximum cluster mass increases with the number of clusters (Whitmore 2003; Larsen 2002). This comes from setting to unity the integral over the

cluster distribution function above the maximum mass: $1 = \int_{M_{max}}^{\infty} n(M)dM$, which gives $A = M_{max}$. Then the total number of clusters is $\int_{M_{min}}^{\infty} n(M)dM \simeq M_{max}/M_{min}$. It is seen that the number of clusters counted down to some conventional minimum mass scales with the maximum mass. If the cluster mass function were a slightly different power law, then this size of sample scaling would be slightly different too.

A second size-of-sample effect is that the maximum mass of all the clusters in a logarithmic interval of age increases linearly with the age. This is because the number of clusters that ever formed, plotted in equal logarithmic intervals of age, increases linearly with age. In fact, low mass clusters often cannot be seen at great age because they are too faint. But this correlation between maximum mass and age does not need to correct for these missing clusters. Many of the largest bound clusters are not likely to disperse until a very old age – older than the disk. This method has been used by Hunter et al. (2003) to derive the cluster mass function in the LMC.

The YMC formation rate may scale with the star formation rate per unit area (Larsen & Richtler 2000) by another size-of-sample effect (Billett et al. 2002). The average star formation rate per unit area scales with the gas column density to the power ~ 1.4 (Kennicutt 1998), and the gas pressure scales approximately as the column density squared. Thus the gas pressure scales as the star formation rate per unit area to the power 1.4. At a given density n that defines a cluster, the cluster mass scales with the pressure as

$$M \sim 6 \times 10^3 \; M_\odot \left(P_{int}/10^8 \; \text{K cm}^{-3} \right)^{3/2} \left(n/10^5 \; \text{cm}^{-3} \right)^{-2}. \tag{1}$$

The normalization for this relation applies to the molecular core near the Trapezium cluster in Orion (Lada, Evans & Falgarone 1997). If $M_{max} \propto P^{3/2}$ also, then $M_{max} \propto$ the star formation rate per unit area through its similar pressure dependence: both M_{max} and SFR/Area $\propto P^{1.4}$ or $P^{1.5}$. This is the maximum mass that can form in a region with a certain pressure.

Such a mass is likely to form if a sufficiently large number of clusters forms that M_{max} is sampled in the ensemble. Considering also the size-of-sample count given above, $N = M_{max}/M_{min}$, we have two definitions for M_{max}: One comes from the ISM pressure, which is related to the star formation rate *per unit area*, and the other comes from the total number of clusters through the product NM_{min}, which depends on the total star formation rate (not per unit area). In a galaxy with small area and a large pressure (a dwarf starburst) the first M_{max} can exceed the second. In this case, only a fraction of these galaxies with high enough pressure to form a YMC will actually do so because of limitations from the small size of the sample. In a very large galaxy with a low total star formation rate, the second M_{max} can dominate the first. Then the maximum cluster mass should be small (because high pressure regions are very rare) compared to the maximum mass expected from the large number of clusters. In this second case, the cluster mass function may end abruptly at a low value of M_{max} (determined by the low pressure), and there should be significantly more clusters than just one at this maximum mass. There are no observations yet of this second size-of-sample effect yet.

Most normal galaxies have a value of M_{max} from pressure limitations that is about the same as the value from the size-of-sample effect. That is, there is

typically a smooth power law of cluster masses up to the one largest cluster. (Exceptions to this were discussed in Sect. 5.). Then the number of YMCs, or the fraction of the uv light in the form of YMCs, increases approximately linearly with the star formation rate. For a sample of galaxies that are all about the same size, as in the Larsen & Richtler (2000) sample (Billett et al. 2002), the fraction of uv light in the form of YMCs also increases in direct proportion to the star formation rate per unit area.

7.   On the origin of the cluster mass function

The characteristic $M^{-2}dM$ mass function of clusters could follow from the hierarchical distribution of gas in a turbulent medium. The densest regions of a random fractal have approximately this mass function (Elmegreen 2002). Figure 1 shows the mass functions of distinct density maxima in a fractal Brownian motion distribution of density that was made in the following way. First a 3D grid in wavenumber-space, (k_x, k_y, k_z), was filled with random complex numbers having real and imaginary values between 0 and 1. This noise was multiplied by a power $-\beta/2$ of the distance to the origin $k = \left(k_x^2 + k_y^2 + k_z^2\right)^{1/2}$. The inverse Fourier transform of this noise cube was taken, giving a cube twice as large in each dimension filled with positive and negative real numbers having a Gaussian distribution. This is a Brownian motion fractal. To simulate the density distribution in turbulence better, another cube is made from the exponential of these positive and negative real values. After this, the numbers are all positive and they have a log-normal distribution, as does the density field in isothermal turbulence (Ostriker, Gammie & Stone 1999; Padoan et al. 2000; Klessen 2000; Ostriker et al. 2001; Li et al. 2003). A clump-finding algorithm was applied to this model density field to get mass spectra. The mass spectra depend on the minimum density that is accepted for a cloud. If the minimum density is very high, then only the densest regions are counted. The result would be most representative of star clusters, which form in the densest part of the turbulent ISM. If the minimum density is low, then the mass function should be more representative of molecular clouds, or perhaps diffuse clouds, which have lower densities compared to the peak.

     On the left in figure 1 four sets of mass distributions are shown, one for each cut-off density that defines the acceptable clouds. The different curves for each are the mass functions for different powers β. A Kolmogorov velocity field would have a power $\beta = 11/3$, which is one of the curves in the figure assuming the same power law for density. Clearly the mass functions are all approximately power laws. Noise at the high mass end where there are only a few clusters prevents an extrapolation there. The power laws steepen as β decreases. A low β fractal has a lot of structure on large wavenumbers, and this means there are proportionally more low mass clumps, giving a steeper mass function.

     The right hand side of figure 1 shows the slopes as a function of β for 4 different density cutoff values. The vertical dashed line is the power spectrum for a Kolmogorov velocity field. The range of observed slopes for the initial cluster mass function (ICMF) is shown. In the model, the slope of the mass spectra of the highest density clumps, which are those with a cutoff density equal to 0.3
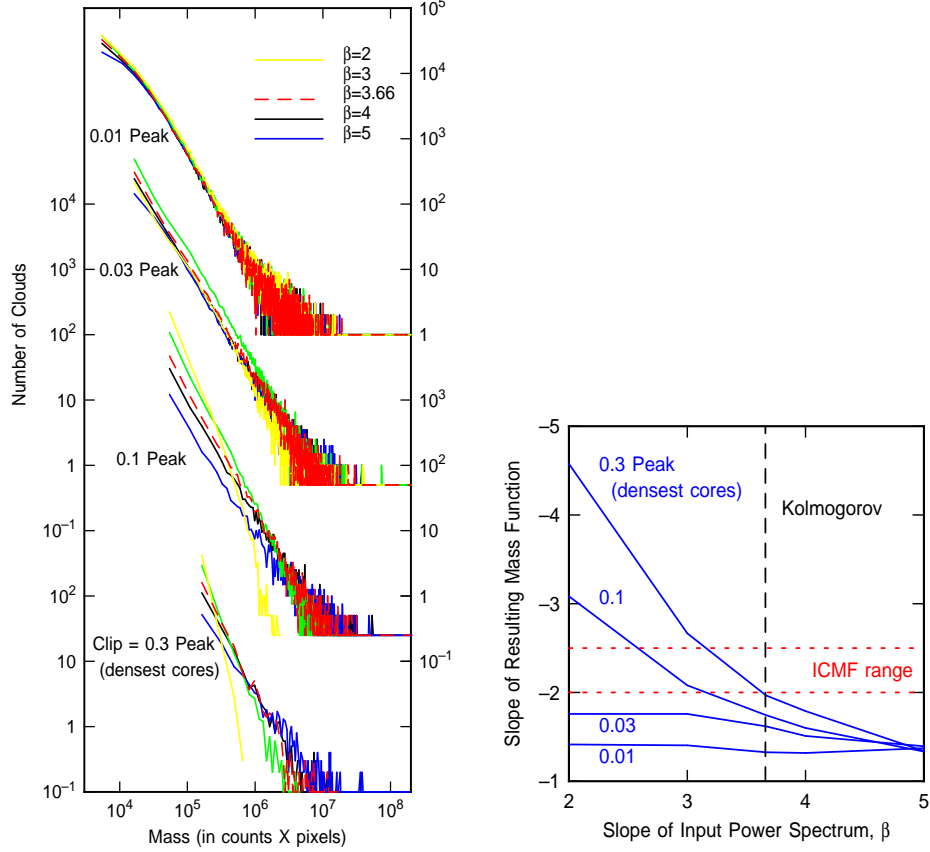
Figure 1. Models of the cluster mass function made from cloud counting in Brownian motion fractals. The thresholds for considering which density maxima are clouds are given in terms of the peak density. The slope of the power law distribution of k^2 in wavenumber space is $-\beta$. The densest peaks, which presumably correspond to the formation of clusters, are for the "Clip=0.3 Peak" case. The mass function slope for these clouds is approximately $M^{-2}dM$ when the power spectrum has a power law corresponding to Kolmogorov turbulence ($\beta = 3.66$). Note how mass spectra are shallower for lower clipping levels, suggesting an origin for the molecular cloud mass spectrum too. This spectrum is shallower than the cluster mass spectrum although both presumably come from the same basic structure of turbulent gas.

times the peak density in the whole fractal, is equal to the observed value of -2 when the power spectrum is Kolmogorov.

This example suggests that clusters that form in the dense regions of a turbulent ISM will have a mass function close to $M^{-2}dM$ as a result of turbulent fragmentation. This type of function is also expected from simpler arguments. For a scale-free density distribution with a hierarchical nature, each clump contains subclumps. If the number of subclumps per clump is constant, then the entire mass of all the gas is present in the summed masses of the clumps on each scale. That is, the smallest clumps contain all the mass, but this same gas is also what comprises the next-smallest clumps, and so on. In this case, the total mass in each equal logarithmic interval of mass is constant, so $M\xi(M)d\log M = $ constant, which means $M\xi(M) = $ constant. Converting the mass function in log intervals, $\xi(M)$, to the mass function in linear intervals, $n(M)$, by writing $\xi(M)d\log M = n(M)dM$, we get $n(M) \propto \xi(M)/M$ and therefore $n(M) \propto 1/M^2$, as observed in figure 1.

8.   Conclusions

Sequential triggering is common in star forming regions. Yamaguchi et al. (1999, 2001a,b) estimate that 10%-50% of star formation in the LMC and Milky Way is triggered by HII regions. However, the triggered regions in the main disks of galaxies are usually too small to make YMCs. Triggering by these same mechanisms but in the nuclear regions of galaxies could make YMCs because the ambient density and pressure are higher there than in the main disks. Or, if there are a very large number of star-forming regions, some few might achieve the high masses and densities required even in the main disks.

Random triggering by stray supernovae or other pressure bursts occurs outside star-forming regions too, but this process is rare and the pressures are usually too weak and too divergent to make YMCs (again, this statement is limited to the main disks of spiral galaxies).

Galaxy-scale processes commonly move around the required gas mass to make a YMC, but these processes are generally too low in pressure to get the required high densities.

The observations of YMCs suggest two triggering mechanisms. One applies to peculiar one-time events and special places that have extraordinarily high energy inputs. These appear to make YMCs without the usual $M^{-2}dM$ power law distribution of lower mass clusters, i.e., to make YMCs almost exclusively. This conclusion is uncertain because the sampling statistics are poor at the present time. Examples include low mass galaxies which, because of their low rotation and rms motions, are loosely bound and somewhat fragile, making them easily perturbed by other small galaxies or intergalactic gas clouds (e.g., Taylor 1997). The dense cores of low mass galaxies also make YMCs, perhaps because of steady accretion from the outer disk and high pressure from self-gravity. The collapsed tips of spiral arms have produced YMCs in two cases, suggesting these regions are more catastrophically unstable than spiral arm midpoints. Tidal shocks in interacting galaxies can make conditions right for YMC formation too by compressing large parts of the ISM for a short time.

Another process that can make YMCs without a proportional number of small clusters is cluster coalescence. Clusters of modest mass that are born with the normal power law distribution of smaller clusters around them may accrete a high fraction of these clusters and become a YMC with few lower mass clusters remaining.

There is also a second formation mechanism for YMCs that contains the normal mix of star formation processes which together produce hierarchical structure and $M^{-2}dM$ power laws (see review in Elmegreen et al. 2000). It applies to extensive galactic regions with high pressures, such as merger remnants, ILR rings and nuclear disks.

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